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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-73

RESEARCH ON THE VOLUME RECOMBINATION OF CESIUM IONS

FINAL REPORT

Task 1D010501A01408
Contract DA 44-177-TC-694(T)

November 1963

prepared by:

RADIO CORPORATION OF AMERICA
Princeton, New Jersey

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HEADQUARTERS
U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

This report reviews and summarizes the work performed under Contract DA 44-177-TC-694 for the U. S. Army Transportation Research Command.

Work on this project was carried out in the David Sarnoff Laboratories, Radio Corporation of America, Princeton, New Jersey, from September 1960 to March 1963, under the overall direction of Dr. Leon Nergaard.

The purpose of this study was to measure experimentally the recombination coefficient of the cesium ions. A unique apparatus was designed and constructed for the purpose of making the experimental measurement. Preliminary measurements have been made. However, refinements in the apparatus are necessary before more precise measurements can be made.

The conclusions reached and the recommendations made in this report are concurred in by this command.

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RESEARCH ON THE VOLUME RECOMBINATION OF CESIUM IONS

FINAL REPORT

for the period

October 1, 1960 to June 30, 1963

Prepared by
Radio Corporation of America
RCA Laboratories
Princeton, New Jersey

Prepared for
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

FOREWORD

The work on this contract in the period of October 1, 1960, through March 31, 1963, is covered by Interim Engineering Report No. 1. Subsequent work is covered in this report. While this report may be read independently of the Interim Engineering Report, a full appreciation of the experiment can be had only by reading both reports.

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INTRODUCTION

A detailed review of the beam method of finding the recombination cross section of ions, as employed in this program, has been given in the Interim Engineering Report No. 1 of the present contract for Research on the Volume Recombination of Cesium Ions.[1] The impetus for this work derives from the fact that recombination plays an important role in the operation of most plasma devices. The rational design of any plasma device (e.g., thermionic energy converters, plasma cathodes, plasma microwave oscillators, plasma thrustors) relies on accurate knowledge of all the significant parameters, including the recombination cross section.

To date, the measurements of recombination have relied on some variation on the theme of measuring the time-rate of decay of a plasma. Recently the time equilibrium of a synthesized cesium plasma has been studied.[12] The rate-of-decay and time equilibrium methods measure the recombination coefficient in a complex plasma whose constituents are not known. The results have been difficult to interpret and have yielded inconsistent values. The present program, supported by the U.S. Army Transportation Corps, measures the atom current formed as an ion beam passes through an electron cloud (recombiner). Since it is possible to mass-analyze the ion beam prior to the interaction, the identity of the interacting species can be determined in advance. Thus, an unambiguous value for the recombination cross section can be obtained. A schematic diagram of the method is shown in Figure 1.

The method has been put into effect without the mass analyzer. The initial measurements do not distinguish directly between atomic and molecular ions. These measurements do, however, show the feasibility of the technique and have given tentative upper bounds on the value of both the recombination cross section for atomic ions (monomers) and for molecular ions (dimers). The molecular recombination (probably dissociative recombination) is distinguished from the atomic recombination by varying the percentage admixture of atomic and molecular ions through temperature control of the chemical cesium generator which feeds the porous tungsten-plug ion source. The dependence of the molecular percentage on the temperature was found by testing the ion source in a mass spectrometer external to the apparatus. A lower bound of 8×10^{10} electrons/cm^3 for the recombiner electron density has been found through the use of a capacitive technique of measuring plasma density. Using this density in conjunction with the preliminary measured recombination currents, an <u>upper</u> bound of 5×10^{-19} cm^2 ($\alpha = 9.1 \times 10^{-12}$ cm^3/sec) has been found for the atomic recombination cross section and 3×10^{-14} cm^2 ($\alpha = 5.4 \times 10^{-7}$ cm^3/sec) for the molecular (dissociative) cross section. The atomic results are in good agreement with the results of Hinnov and Hirschberg.[2] The molecular results are of the same order as theoretical predictions for dissociative recombination.[3]

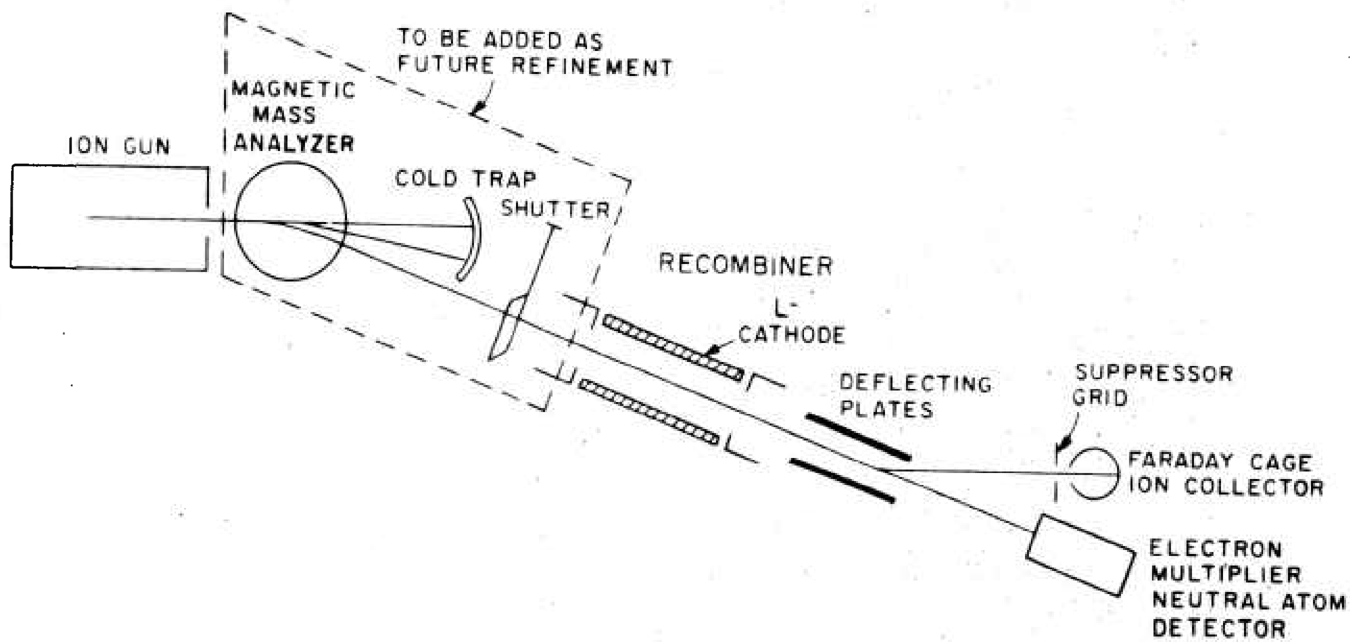

Figure 1. Schematic Diagram of the Apparatus.

In the following sections the additions and modifications made to the recombination apparatus subsequent to the issue of Interim Engineering Report No. 1 will be described. The results of the measurements made to date will be presented and discussed. Recommendations for future work in this area are then made.

THEORY OF METHOD-EXTENSION

A. EXTRACTION OF ATOMIC AND MOLECULAR CROSS SECTIONS FROM DATA

As was shown in the first report, the cross section for recombination (Q_R) can be found by measuring the current of recombined atoms (I_R) produced when an ion beam of current I_o passes through an electron "cloud" of effective density N_e and length x. The relation is $Q_R = I_R/I_o N_e x$.

If the ion beam were to consist of a mixture of atomic and molecular ions, the current of recombined atoms (assuming the molecular recombination was dissociative) is given by

$$I_R = I_a N_e Q_R x + 2 I_m N_e Q_m x \quad , \tag{1}$$

where I_a is the atomic-ion current,
I_m is the molecular-ion current, and
Q_m is the dissociative recombination cross section.
The factor of 2 in the second term takes account of the dissociation of each molecular ion into two atoms. Let $I_m = \delta I_a$ and $I_o = I_a + I_m$. Then, if I_R is measured for two values of δ (δ_1 and δ_2) while I_o is held constant (or I_R is normalized to constant I_o), it is readily shown from (1) that

$$Q_R = \frac{\delta_2 (1 + \delta_1) I_{R_1} - \delta_1 (1 + \delta_2) I_{R_2}}{N_e I_o x (\delta_2 - \delta_1)} \tag{2}$$

$$Q_m = \frac{(1 + \delta_1) I_{R_1} - (1 + \delta_2) I_{R_2}}{2 N_e I_o x (\delta_1 - \delta_2)} \quad . \tag{3}$$

Thus, by controlling the percentage of molecular ions, both the atomic and molecular recombination cross sections can be obtained from equations (2) and (3).

B. CAPACITIVE METHOD OF FINDING A LOWER BOUND ON THE RECOMBINER ELECTRON DENSITY

As has been pointed out by Ash and Gabor,[4] a lower bound on the electron density in the recombiner may be obtained by measuring the change in capacitance between a probe and the recombiner as an ion sheath is formed around the probe when the probe is made negative with respect to the plasma. For frequencies well below the electron plasma frequency, the plasma may be considered a good conductor. Thus, the capacitance between the probe and the plasma when a sheath is formed is close to that which would be measured between the probe and a conductor located a sheath thickness away. In the recombination experiment, it is desirable to measure the recombiner density while the ion beam is operating. To do this the aperture plates are used as probes (see Figure 2). The effective area for the aperture plates when used as capacitive probes is taken to be the cross-sectional area of the recombiner cathode. If d is the diameter of the cathode, the effective area, A, is $2(\pi d^2/4)$ for the two aperture plates connected in parallel. If there is no plasma present, the capacitance between the aperture plates and the recombiner is $C_1 = \epsilon_o A/S$. Here S is the separation between the aperture and the recombiner and ϵ_o the permittivity of free space. With a plasma present and a sheath formed, the effective separation is reduced to the sheath thickness, which can be no less than one Debye length, λ_D. Thus, the new capacitance is at most $C_2 = \epsilon_o A/\lambda_D$. The change in capacitance, $\triangle C$, when the plasma is turned on is $C_2 - C_1$ and

$$\triangle C \leq \epsilon_o A \left(\frac{1}{\lambda_D} - \frac{1}{S} \right) . \tag{4}$$

If the Debye length, $(\epsilon_o kT/2 N_e e^2)^{1/2}$, is substituted in (4), one obtains

$$N_e \geq \frac{kT}{2 e^2 A^2 \epsilon_o} (\triangle C)^2 + \frac{\epsilon_o kT}{2 e^2 S^2} \tag{5}$$

Thus, by measuring the change in capacitance between the two aperture plates and the recombiner cathode as a sheath is formed by making the apertures negative, one may apply equation (5) to find a lower bound on the electron density in the recombiner.

THE RECOMBINER

The recombiner in its present form is illustrated in Figure 2. Electrons are emitted from the heated L-cathode and are partially neutralized by positive barium and cesium ions. The cesium ions are formed by the surface ionization of background cesium atoms on those areas of the tungsten cathode that are not covered by barium. When the L-cathode is operated below the optimum temperature for the emission of electrons, substantial areas of tungsten remain uncovered. As a result, the plasma properties of the recombiner are optimized at approximately 900°C. This may be compared to the 1050-1100°C necessary for best electron emission. Because the background cesium pressure is increased when the ion gun is operated, as compared with the situation when the ion gun is cold, it is necessary to measure the electron density with the ion beam operating. This has been done by the capacitive method described earlier in this report. A plot of $\triangle C$ versus the negative voltage applied to the apertures through a 300-KΩ dropping resistor is given in Figure 3. Because the apertures are heated by the cathode and emit electrons, the actual retarding voltage between cathode and aperture is only a small fraction of the applied voltage. The larger part of the voltage is dropped in the 300-KΩ resistor.

In a typical plot, $\triangle C$ is zero until the applied voltage is sufficiently negative to form a sheath. At this value, $\triangle C$ increases suddenly to its peak value. Further increase in the negative voltage causes the sheath to increase in size and $\triangle C$ drops. The highest value of $\triangle C$ (16.3×10^{-12} farad) occurs at $T_c = 900°C$. Using this value of $\triangle C$ in equation (5), a lower bound of 8×10^{10} electrons/cm^3 is found for the recombiner electron density. When the ion beam is shut off, a similar measurement gives a $\triangle C$ of 5×10^{-12} farad and hence a lower bound of 7.5×10^9 electrons/cm^3. This clearly demonstrates the role played by the background cesium in setting the plasma conditions in the recombiner.

When recombination measurements are made, the electron plasma is turned off by applying an axial magnetic field of approximately 100 oersteds to the recombiner. The field is produced by two coaxially wound coils of high-temperature ceramic-insulated copper wire. The coils are connected so that their fields add in order to turn off the electrons and so that their fields oppose when the plasma is to be on. Switching is done in this manner so that there will be no change in coil temperature, hence, no possible change in background pressure in going from the off to the on position and vice versa.

Provisions have been made, although not yet tested, to measure the recombiner electron density by use of the electron-beam-plasma interaction.[5-8] Helices capable of coupling rf energy to and from an electron beam over a range of frequencies in the 2 to 4-Gc band have been placed before and after the recombiner. The ion gun is capable of being

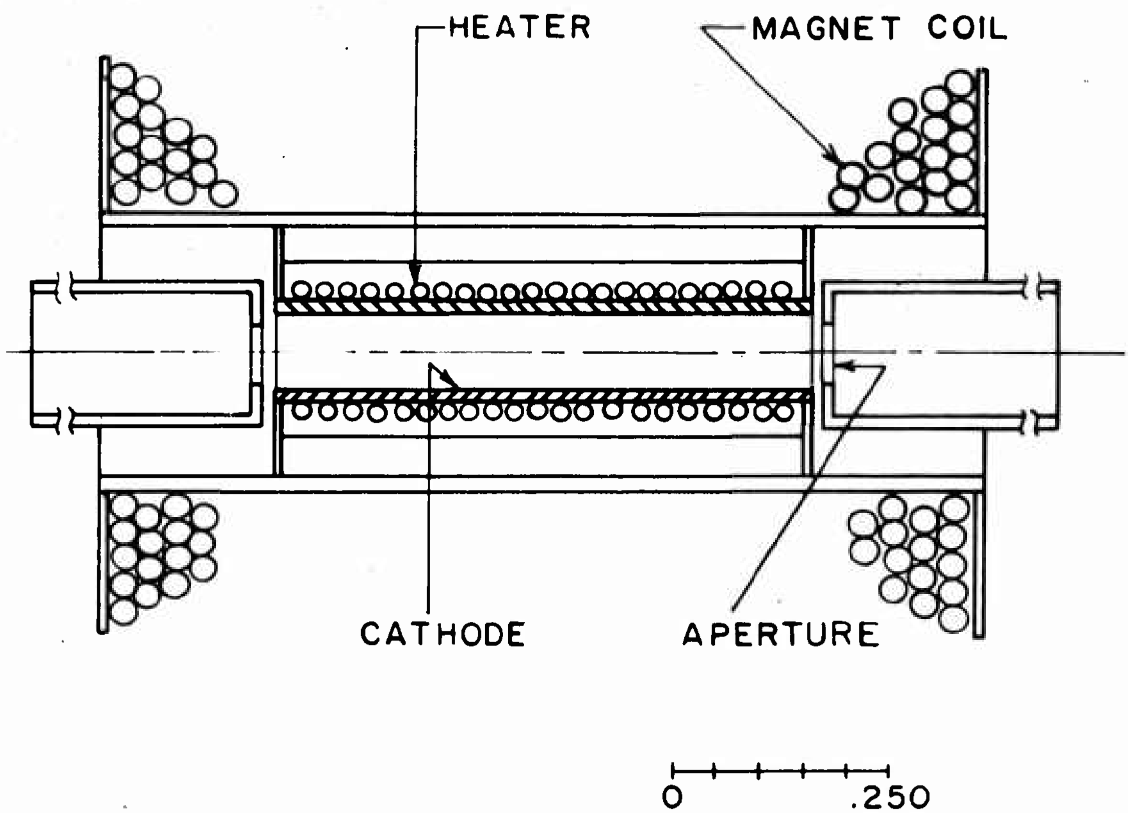

Figure 2. Recombiner Assembly.

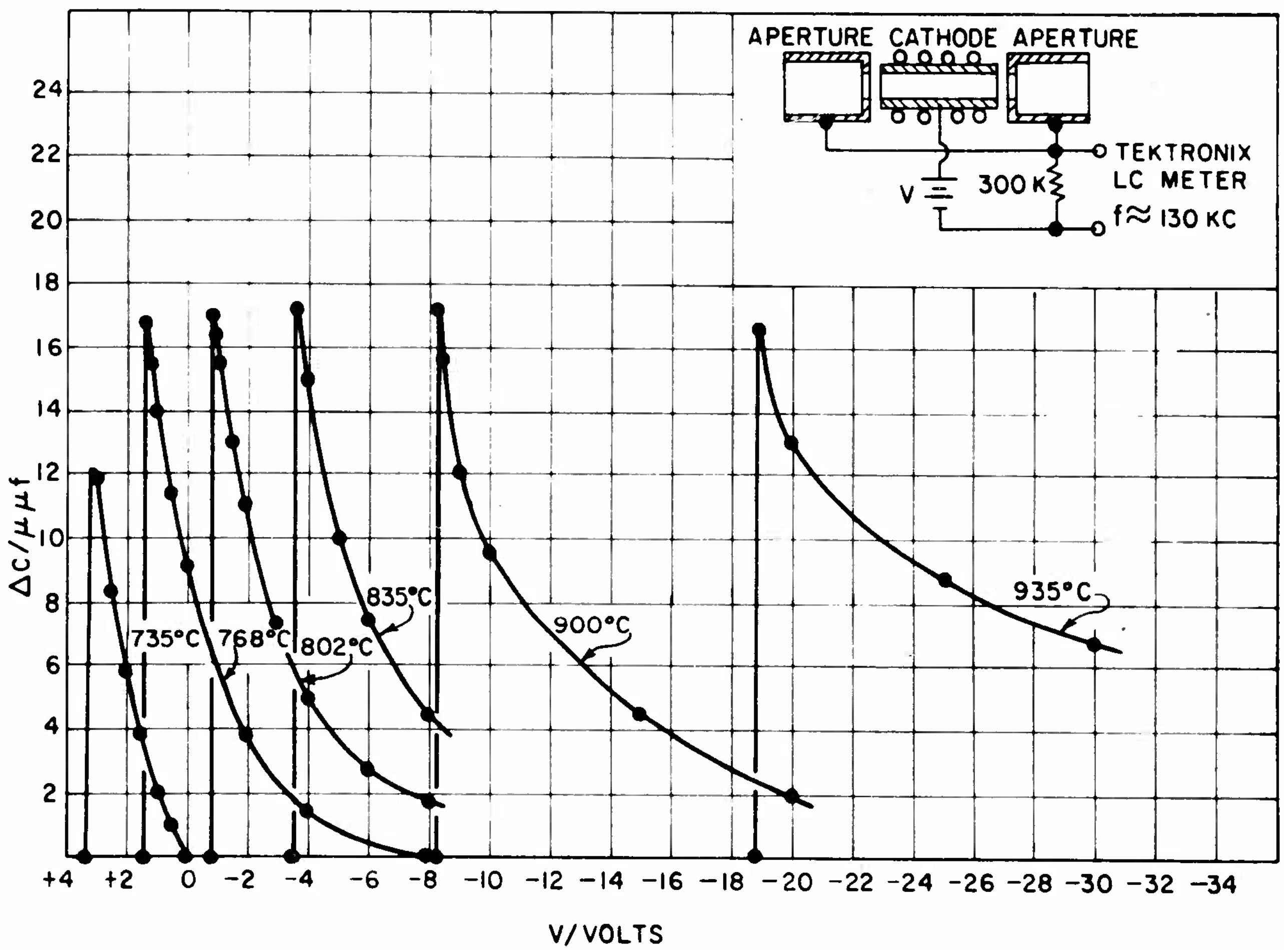

Figure 3. Plot of $\triangle$C vs. V (Illustration of Measuring Setup in Inset).

operated as an electron gun. Thus, an electron beam can be modulated by the first helix, interact with the plasma in the recombiner, and be detected by the second helix. If the electron beam is modulated near the plasma frequency ($\omega_p^2 = e^2 N_e/m\,\epsilon_o$), the signal on the beam will be amplified by the plasma. Thus, by observing the frequency which maximizes the difference in transmission between the case of the plasma on and the case of the plasma off, the electron density may be obtained. The electron density can change when the ion beam is turned off and the electron beam on, despite the fact that the cesium-source conditions need not be altered to convert from ion to electron emission. To overcome any such variation, fast pulsing techniques may be employed. Then the plasma frequency measurement can be made before the plasma has had time to undergo appreciable change.

THE ION SOURCE

As was indicated in the first report, the cesium alumino-silicate ion source proved to be insufficient in stability and emission. In its place, a porous tungsten-plug type of ion source fed by a chemical generator of neutral cesium has been developed and used. The ion source is illustrated in Figure 4. Neutral cesium is generated when the mixture of one part cesium chromate and two parts silicon is heated to the vicinity of 750°C by the generator heater. The cesium passes the quartz wool-tungsten wool "filter" and is ionized by resonance ionization in going through the porous tungsten plug, which is heated to the neighborhood of 1000°C by the plug heater. The heat sinks and length of tubing connecting the generator to the tungsten plug provide thermal isolation. This arrangement allows independent control of the neutral cesium pressure via control of the generator heater and of the plug temperature through control of the plug heater. The temperature of the plug sets the temperature of the neutral cesium gas in the vicinity of the plug. After the generator has been operated for even a few minutes, there is a supply of metallic cesium sufficient to operate the ion source for a few hours without further operation of the generator heater. This structure provides a copious (greater than 1 ma/cm^2) and stable supply of cesium ions. The ion gun incorporating the porous plug ion source is shown in Figure 5. The ion optics has not been changed from that used in the gun which employed the silicate type of ion source. At a beam voltage of 5 kV, over one microampere of ion current has been focused with less than 2×10^{-4} microamperes of interception on the recombiner apertures. Typical voltages applied to the present ion gun are V_1 = 5 kV, V_2 = 4.4 kV, V_3 = 0.5 kV, V_4 = 2.7 kV, and V_5 = 0 (ground).

Mass spectrometer tests have been made on the porous plug cesium ion source. The tests were performed by J. R. Woolston and E. M. Botnick of RCA Laboratories using an M.S.-7 mass spectrograph. As can be seen in Table 1, the source has reasonably high purity. The relatively large admixture of the dimer Cs_2^+ (18 parts per million) when the generator is at a high temperature as compared with the case when the generator is cool (< 0.4 parts per million) can be readily understood. The formation of Cs_2 will be a function of the cesium pressure (and hence of the generator temperature) on the interior of the source. The greater the pressure, the greater will be the percentage of neutral cesium molecules which impinge on the porous tungsten plug. A fixed small percentage of the Cs_2 will ionize to become Cs_2^+. The greatest portion of the dimer will, however, dissociate upon contact with the heated high-work-function surface, since the dissociation energy of Cs_2 is approximately 0.45 eV[9] while its ionization energy is 3.25 eV.[10] The fact that the yield of the cesium molecular ion can be varied by more than a factor of 40 through control of the generator temperature allows both the molecular and atomic recombination to be estimated through the use of equations (2) and (3).

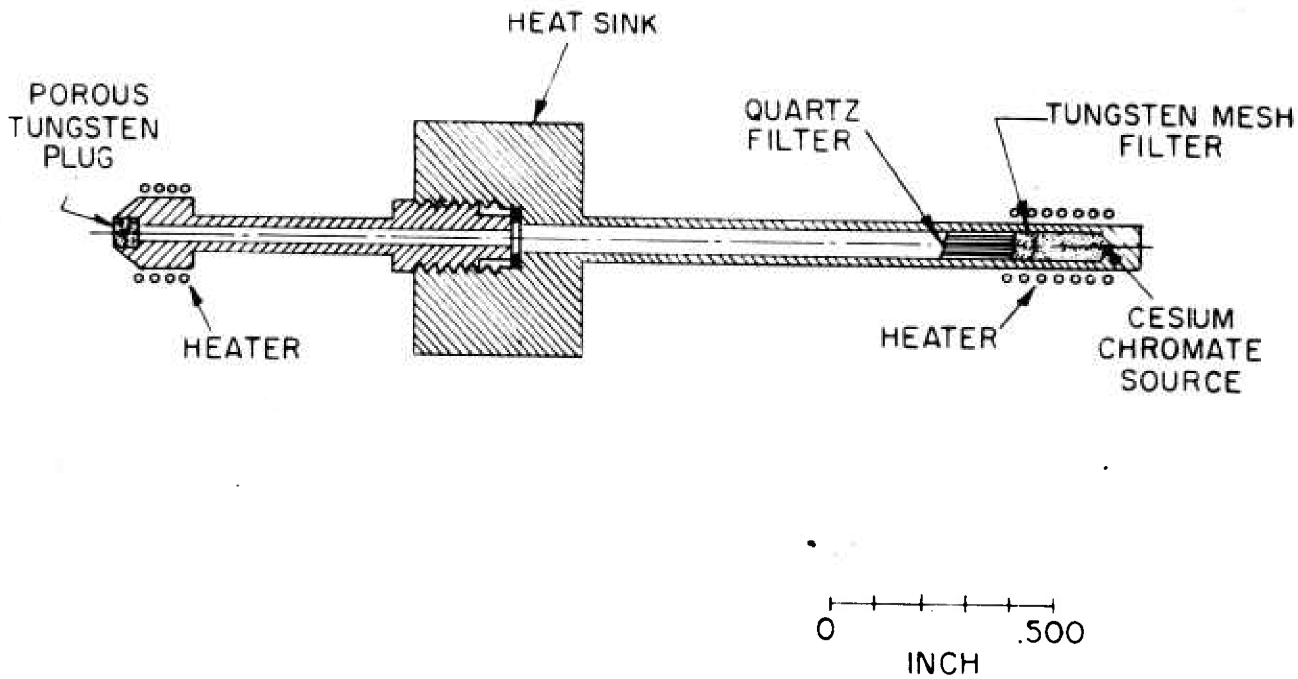

Figure 4. Porous Plug Cesium Ion Source.

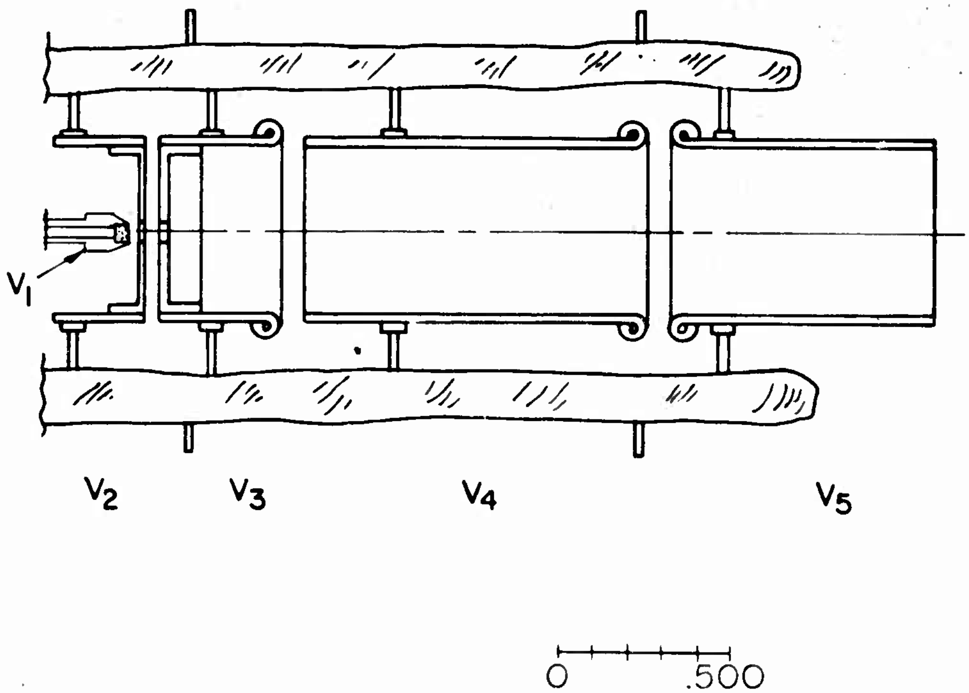

Figure 5. Ion Gun With Porous Plug Cesium Ion Source.

TABLE 1.

ANALYSIS OF CESIUM ION SOURCE

Cesium Ions (Heater Current at 0.0)

	ppm*
Cs_2^+	<0.4
Cs_2O^+	<0.4

Cesium Ions (Heater Current at 2.0 - 3.0 amps)

	ppm
Cs_2^+	18.0
Cs_2O^+	1.3

Other Ions in Mass Spectrum (Heater Current at 2.0 amps)

M/e	Identification	ppm	M/e	Identification	ppm
12	C	0.3	52	Cr	3
14	N	0.2	55	Mn	3
16	O	2	56	Fe	30
18	H_2O	1	58	Ni	0.3
20	Ca_2?	1	64	Zn?	0.2
23	Na	20	70, 72	Not Ge?	1
24	Mg	200	85	Rb**	3000
27	Al	1500	88	Sr	2
28	Si	3	98	Mo	40
39	K**	1200	114	Cd	30
40	Ca	50	138	Ba	10
42, 43, 44	Hydrocarbons?	1 each	~155	?	1
48	Ti	1	184	W	10
51	V	0.3	210	WO	3

* Average values in parts per million (Cs^+ taken as unity).

** The rather large concentrations of K and Rb are attributed by Woolston to the fact that, just prior to the analysis of the recombination source, he had made thermal analyses of K and Rb. Apparently, the spectrograph takes a rather long time to "forget" previous analyses.

The molecular yield of 18 parts per million can provide a molecular-ion beam of sufficient intensity to allow a future direct measurement of the very large dissociative recombination cross section. For this purpose, the atomic ions will be separated from the molecular ions by a mass analyzer internal to the apparatus as indicated in Figure 1.

EXPERIMENTAL METHOD AND RESULTS

The method of taking data is extremely important since it is necessary to avoid the recording of signals which may result from spurious effects. High-energy neutral atoms are produced by exchange between the ions and the background gas in the apparatus.. Thus, in order to observe the recombination, one must turn the recombiner on and off and observe the change in the neutral atom current reaching the detector. If, however, the turning on and off of the recombiner by means of the magnetic field affects the background pressure in the apparatus, a change in neutral current will be produced because of the ion exchange interaction. Fortunately, the detector, which relies on the production of secondary electrons by the impact of the energetic atoms with the copper beryllium first dynode of an electron multiplier, is insensitive to low-energy neutral background current.

To demonstrate that the observed change in signal is indeed due to recombination, a number of subsidiary tests are made. The approach will perhaps be clearest if a sequential description of a typical run is given.

The apparatus is assembled and evacuated. It is then carefully leak-checked and pumped to a good vacuum. The system is then baked at 400°C for at least three hours and is pumped until the pressure reaches the low 10^{-9} mm Hg range. Thereupon, the recombiner cathode is activated in the conventional way. The magnet coils are operated with more than normal operating current so that they are fully degassed. For the same reason, the porous-plug heater and then the generator heater are also operated at levels somewhat above the normal operating range. Finally, all the heaters and the magnet coil are operated simultaneously at high temperature until the pressure in the system is below 5×10^{-8} mm Hg. The temperatures are then readjusted to the desired values and tests can begin.

At this point, the ion beam is focused so that the interception on the apertures is minimized (less than 2×10^{-4} microamperes). Because of electron current flow between the apertures and cathode of the hot recombiner, it is necessary to check the focus of the ion beam with the recombiner cold. The deflector and suppressor voltages are applied so that the ion beam is collected in the ion collector. Under these conditions (recombiner cold), the multiplier output and the ion collector current are observed as the magnet coil is turned on and off (recollect that this is done by alternately connecting the coils so that their fields add and then oppose—thus the coil temperature is not affected). Under conditions of optimum ion beam focus, <u>no change</u> in the multiplier output is observed as the magnet is turned on and off with the recombiner cold.

Following this test, the recombiner is heated to the desired operating temperature (900°C) and the ion beam is turned off in two ways: by turning off the porous-plug heater and by turning off the high-voltage supply (porous-plug heater on). For each of these conditions, the magnet coil is turned on and off and the multiplier output checked. In neither case is any change observed in the output.

Finally, the ion beam is turned on and reset to its condition of optimum focus (a master switch allows the ion beam to be turned on and off without disturbing the voltage settings). With the recombiner cathode heated, both the multiplier output and the ion collector current (I_o) are observed as the recombiner magnet coil is once again turned on and off. In this last case, no change is observed in I_o, but an increase is observed in the multiplier output when the recombiner is in the on condition (magnet field zero). The results of the tests just described are summarized in Table 2.

It is clear from Table 2 that no signal is obtained unless the ion beam and the recombiner are operating. This latter, taken in conjunction with the constancy of the current to the ion collector, provides very strong evidence that the effect being observed as the recombiner magnet field is turned on and off is due to recombination.

TABLE 2

SUMMARY OF TESTS MADE TO CHECK FOR SPURIOUS SIGNAL. DEFLECTING VOLTAGE IS ON FOR ALL CONDITIONS.

Condition	Recombiner Heater	Ion Gun		Change as magnetic field goes from on to off?	
		High Voltage	Heater	Ion Current	Multiplier Output
A	OFF	OFF	OFF	NO	NO
B	OFF	ON	ON	NO	NO
C	ON	OFF	OFF	NO	NO
D	ON	ON	OFF	NO	NO
E	ON	OFF	ON	NO	NO
F	ON	ON	ON	NO	INCREASES

To actually take data, a number of on-off trials are made and the average change in the multiplier output is obtained. The nominal multiplier sensitivity is found by allowing the ion beam, reduced in current to a value which will not saturate the multiplier, to impinge directly on the first dynode. The gain is then the ratio of the multiplier output to the ion current input. For the present, it is assumed that the gain for atoms will be the same as for ions. (See pages 15 and 16 of the Interim Engineering Report No. 1.[1] The calibration techniques mentioned there have not as yet been incorporated in the apparatus.) Using the "gain", the current of recombined atoms I_R can be obtained from the data. For convenience of computation, the various values of I_R are normalized to a common value of ion beam current (1μamp). The data on recombination that have been obtained to date are given in Table 3. They represent the results of preliminary measurements. It is expected that many additional measurements over a wide range of operating conditions will be made in subsequent months.

TABLE 3

CESIUM RECOMBINATION DATA AND RESULTS

Date	No. of on-off Readings	Cesium Generator Heater Current	Exchange Current I or I_i=1μa (Amperes)	Recombination Current for I_i=1μa (Amperes)	I_R/I_{ex} (Percent)
2/21/63	10	0.0	15.9×10^{-13}	7.3×10^{-14}	4.6
2/22/63	12	2.0	18.5×10^{-13}	15.5×10^{-14}	8.4
2/25/63	8	0.0	4.5×10^{-13}	4.7×10^{-14}	10.4
2/26/63	12	0.0	18.4×10^{-13}	7.4×10^{-14}	4.0
2/26/63	13	2.0	13.0×10^{-13}	13.8×10^{-14}	10.6
2/26/63	12	2.0	11.1×10^{-13}	21.8×10^{-14}	19.8

Average Values

Cesium Generator Heater Current	Average Values of I_R for I_i = 1μa/Amps.	Ratio of Molecular to Atomic Current = δ
0.0	6.44×10^{-14}	0.4×10^{-6}
2.0	17.0×10^{-14}	1.8×10^{-5}

From equation (2) and (3) and using the peak value of $Ne \geq 8 \times 10^{10}$ electrons/cm^3 as given in the recombiner section with x = 1.52 cm,

Atomic Recombination $Q_R \leq 5 \times 10^{-19}$ cm^2, $\alpha_R \leq 9.1 \times 10^{-12}$ cm^3/sec

Molecular Recombination $Q_m \leq 3 \times 10^{-14}$ cm^2, $\alpha_m \leq 5.4 \times 10^{-7}$ cm^3/sec.

DISCUSSION

Perhaps the most important result which has thus far been achieved is the demonstration that the beam method of measuring recombination has sufficient sensitivity to do just that. With no ion beam current flowing, the output of the multiplier (dark current) has been reduced to values which are at least an order of magnitude below the exchange current. Thus, the chief source of noise is the current due to exchange. Since, as can readily be seen in Table 3, the recombination current is around 10 percent of the exchange current, little difficulty has been encountered in making the measurement. This favorable situation can be attributed largely to the comparatively high electron densities achieved in the recombiner. Since the electron density is obtained by creating what is probably a partially neutralized plasma, the effect of the plasma ions on the experiment must be considered. The fast cesium ions can undergo a number of different types of collisions in passing through the recombiner. The coulomb collisions (elastic) between the fast ions and the plasma electrons can have no effect on the experiment; the electron can impart very little momentum to the ions (energy transfer going as M/m), and those electrons which receive large momentum cannot pass the deflecting plates to reach the multiplier. The elastic collisions between fast and slow ions can impart relatively high transverse velocities to the particles involved. The aperture geometry is, however, arranged to prevent ions originating in or passing through the recombiner from traversing the deflecting plates and reaching the multiplier as long as the deflecting voltage is on. Thus, the only effect of elastic ion-ion collisions will be to add a small noise component, similar to partition noise, to the ion current. Inelastic ion-ion and ion-neutral atom collisions other than exchange can possibly result in radiation of high enough frequency to cause photoemission from the multiplier dynode. It should be recalled that we deal with an electron multiplier, not a photomultiplier. The photoelectric work function of the copper-beryllium first dynode is of the order of 4.0 volts. It would be unusual if the quantum efficiency of this surface were greater than 10^{-3} even for wavelengths well above the threshold. This is compared with the 3 electrons per incoming 6-kV cesium ion which the dynode provides (see Interim Report No. 1). Thus, it is very conservative to say that only inelastic collisions which result in quanta of energy greater than 4 eV (wavelengths less than approximately 3,100 Å) and which have cross sections greater than $10^3\ Q_R\ N_e/N_u$ can make significant contributions to the signal. Here N_u is the density of the ions or atoms with which the fast ion (ion beam) makes an inelastic collision.

At a pressure of 5×10^{-8} mm Hg, the density of neutral atoms will be 2×10^9. Thus, the cross section for excitation required to cause a significant error in the result is 8×10^{14} cm^2. Excitation cross sections to a particular level are usually[11] of the order of 10^{-18} cm^2. Thus, the radiation from fast ion-neutral atom collisions can be ignored.

Based on the results of the plasma density measurements, the dominant ion which helps to neutralize the space charge in the recombiner is C_s^+. If we assume that the density of C_s^+ is the same as the electron density (it is more likely that the recombiner is only partially neutralized), it would still be required that the excitation of the C_s II lines by impact between C_s^+ ions have a cross section greater than 5×10^{-16} cm^2, and this is exceedingly unlikely. Finally, all the production of radiation by radiative recombination between the plasma electrons and the slow cesium ions can result only in quanta with energies below 4 eV. No photoelectrons can thus be produced by this latter radiation. As a result of these considerations, it seems unlikely that the presence of a partially neutralized electron plasma rather than an electron cloud in the recombiner has any significant adverse effect on the beam method of measuring recombination.

The actual results obtained are not considered to be definitive values since a relatively small number of runs have been made and the calibration procedures are not complete. Thus, it is not yet proper to make detailed comparisons with either theory or other experiments. Nonetheless, it is very heartening that the value found as an upper bound for the atomic recombination agrees to within a factor of two with the values given by Hinnov and Hirschberg.[2] This, of course, implies that a two-electron one-ion three-body type of recombination plays an important role. Similarly, we are encouraged by finding order-of-magnitude agreement between the limiting value of the dissociative recombination measured here and the results of Bates' theory[3] (which, in turn, agrees with certain microwave measurements; see Interim Report No. 1 for a detailed review.). The error is probably rather high in the value obtained here for the molecular recombination, since the technique depends strongly on knowledge of the proportion of ions; yet this proportion was calibrated external to the apparatus.

CONCLUSION

The beam technique of measuring cesium recombination has been demonstrated to work, and initial measurements of upper bounds on the cross sections for both the atomic and the molecular (dissociative) recombination have been found. The atomic cross section is less than or equal to 5×10^{-19} cm^2, and the molecular cross section is less than or equal to 3×10^{-14} cm^2. These are the first direct measurements of recombination cross sections ever made.

RECOMMENDATIONS FOR FURTHER WORK

The following are recommendations for further work:

1. Continuation of Data Taking

2. Calibration of Atom Detector

A technique of using charge exchange either by passing an ion beam through a thin foil or by reflecting ions from a surface at a grazing angle of incidence should be applied to calibrate the atom detector.

3. Measurement of Recombiner Electron Density

An attempt to apply the electron-beam-plasma interaction to the measurement of the electron density in the recombiner should be made. The results can be compared with the results of the capacitive technique already employed.

4. Separation and Identification of the Ion Species Actually Undergoing Recombination

When the calibration techniques have been well established, a mass spectrometer section should be added to the apparatus ahead of the recombiner. Measurements on the atomic and the molecular (dissociative) recombination cross sections can then be made with full knowledge of the indentity of the particular species being investigated.

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Unclassified Report

The feasibility of the ion beam method of measuring the recombination cross section of cesium ions is demonstrated. Preliminary results are given. The atomic recombination cross section of C_s^+ is less than or equal to $5x10^{-19}$ cm^2, while the molecular (dissociative) recombination cross section of Cs_2^+ is less than or equal to $3x10^{-14}$ cm^2.

The method is described briefly and the results are presented in detail and discussed.

1. Cesium ions
2. Recombination reaction
3. Atom recombination

I. Task No. 1D010501A01408
II. Contract DA-44-177-tc-694(T)
III. RCA Laboratories, Princeton, New Jersey
IV. J.M.Hammer, J.J.Thomas, B.B.Aubrey
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